

Influence of cosmic-ray variability on the monsoon rainfall and temperature

Badruddin & Aslam, O.P.M.

Aligarh Muslim University, Aligarh, India-202 002

Abstract

We study the role of galactic cosmic ray (GCR) variability in influencing the rainfall variability in Indian Summer Monsoon Rainfall (ISMR) season. We find that on an average during 'drought' (low ISMR) periods in India, GCR flux is decreasing, and during 'flood' (high ISMR) periods, GCR flux is increasing. The results of our analysis suggest for a possibility that the decreasing GCR flux during the summer monsoon season in India may suppress the rainfall. On the other hand, increasing GCR flux may enhance the rainfall. We suspect that in addition to real environmental conditions, significant levitation/dispersion of low clouds and hence reduced possibility of collision/coalescence to form raindrops suppresses the rainfall during decreasing GCR flux in monsoon season. On the other hand, enhanced collision/coalescence efficiency during increasing GCR flux due to electrical effects may contribute to enhancing the rainfall. Based on the observations, we put forward the idea that, under suitable environmental conditions, changing GCR flux may influence precipitation by suppressing/enhancing it, depending upon the decreasing/increasing nature of GCR flux variability during monsoon season in India, at least. We further note that the rainfall variability is inversely related to the temperature variation during ISMR season. We suggest an explanation, although speculative, how a decreasing/increasing GCR flux can influence the rainfall and the temperature. We speculate that the proposed hypothesis, based on the Indian climate data can be extended to whole tropical and sub-tropical belt, and that it may contribute to global temperature in a significant way. If correct, our hypothesis has important implication for the sun - climate link.

Keywords: sun-earth connection, galactic cosmic rays, summer monsoon rainfall, temperature

1. Introduction

The Asian summer monsoon is the largest single abnormality in the global climate system (Shukla, 2007). The seasonal rainfall brought by the southwest Indian summer monsoon supplies 80% of Southeast Asia's annual precipitation and is vital to sustaining the region's agriculture which supports nearly a quarter of the world's population (Sinha et al., 2007). Indian summer monsoon is one of the main weather systems on earth and variations in its intensity have broad economic effects. It has been the most important climate event in India. Rainfall over India is subject to a high degree of variations leading to the occurrence of extreme monsoon rainfall deficient (drought) or excess (flood) over extensive areas of the country. Floods and droughts result in many losses of lives, crops etc.; these play havoc to Indian economy and society.

Cause of abnormal variabilities in monsoon rainfall (floods and droughts) is not completely understood. Consequently, accurate prediction of rainfall and its variability during monsoon season has been a challenging task. Thus, there is greater need to understand the nature and variability of monsoon climatic conditions, especially, whether there is any extra-terrestrial influence (e.g. cosmic ray variability) in addition to natural terrestrial climatic conditions. More specifically, it is important to know whether Indian monsoon rainfall is significantly influenced by changes in cosmic ray flux, and whether climate cooling is an effect of cosmic ray flux change. If so, then the possible physical mechanism(s) must be identified.

It is well known that cosmic ray flux varies in anti-phase with solar activity over all time scales. On the longer time scales (millennial, centennial and multi-decadal), a number of studies have suggested solar/cosmic ray variability influence on the intensity of monsoonal rainfall in tropical and sub-tropical regions with conflicting results. For example, low rainfall in India coinciding with low solar activity (or high cosmic ray intensity) (e.g. Agnihotri et al., 2002; Tiwari et al., 2005; Gupta et al., 2005; Yadava and Ramesh, 2007) and in North Africa and South Oman (Neff et al., 2001). These results imply that increased galactic cosmic ray (GCR) intensity is associated with a weakening of the monsoon (decreased rainfall) (Kirkby, 2007; Singh et al., 2011). In contrast, low rainfall in equatorial East African (e.g. Verschuren et al., 2000), weaker Chinese monsoon (Hong et al., 2001), and low tropical rainfall in Gulf of Mexico region have been observed, during high solar activity (or low cosmic ray intensity). Occurrence of periods of enhanced monsoonal precipitation in India slightly after the termination of the Wolf, Sporer and Maunder minima periods (low solar activity/high cosmic ray intensity) have been reported by Khare and Nigam (2006). This finding is in agreement with the finding of earlier workers, who reported high lake levels from Mono Lake and Chad Lake in the vicinity of solar minima (cosmic ray maxima) as well as the Nile River in Africa (Ruzmaikin et al., 2006). Thus there are evidences, although sometimes contrary in nature, that suggest for some cosmic ray influence on monsoon rainfall on multi-decadal, centennial and

millennial time scale.

On shorter time scales (decadal to inter annual) too, solar activity/cosmic ray intensity influence on the rainfall changes in Indian summer monsoon have been suggested, but with conflicting results (e.g. see Jagannathan and Bhalme, 1973; Bhalme et al., 1981; Hiremath and Mandi, 2004; Bhattacharya and Narasimha, 2005; Badruddin et al., 2006, 2009).

Understanding the factors that control ISMR onset, its variability and intensity are highly desired. In particular, it is extremely important to know about the role of extra-terrestrial sources (e.g. cosmic rays) in initiating and/or influencing the intensity of rainfall directly (e.g. by changing the collision/coalescence efficiency in rain clouds) or indirectly (e.g. by altering the low cloud amount). It is particularly important to search for connection, if any, between the extreme deficiency (droughts) or excess (floods) in Indian summer monsoon rainfall and cosmic ray flux variability during the same ISMR periods, even though it is widely accepted that Indian monsoon onset and intensity are controlled by large scale atmospheric (e.g. land-sea temperature contrast) and global features (e.g. ENSO, QBO etc.).

Several studies have shown that the warm phase (El Nino) is associated with weakening of Indian monsoon with overall reduction in rainfall while the cold phase (La Nina) is associated with the strengthening of the Indian monsoon with enhancement in rainfall (e. g., Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983). All the El Nino events during 1958-1988 were reported to be droughts and all the La Nina events were associated with excess ISMR. However, weakening of ENSO-ISMIR relationship after 1988 were reported in later studies (e. g., Kripalani and Kripalani, 1997; Kumar et al., 1999; Ashok et al., 2001; Kripalani et al., 2003). Further, for the 14 consecutive years beginning with 1988 (1988 to 2001), there were no droughts, despite the occurrence of El Nino (Gadgil et al., 2004). Although 9 out of 12 drought years identified by us can be associated with El Nino events, and 9 out of 12 flood years with La Nina events, there are reports (Kumar et al., 2002) that out of 22 large negative ISMR anomalies that occurred during 1871-2001, only 11 were associated with El Nino, while out of 19 large positive ISMR anomalies that occurred during the same period, only 8 were associated with La Nina. Therefore, large deficient/excess ISMR does occur in the absence of El Nino/La Nina and we do not yet understand adequately the response of monsoon to El Nino (Gadgil et al., 2004). Thus, there is the possibility of drought/floods in India being influenced by other external agents also.

Cosmic rays are the only source of ion production in the lower atmosphere. There are suggestions that cosmic ray flux variability may influence the earth's climate also. In view of these suggestions, although controversial, it will be interesting to search for any possibility of a link between GCR and rainfall variability. Variations in precipitation potentially caused by changes in the cosmic ray flux have implications for the understating of the cloud and water vapour feedbacks. It is possible that any particular (e.g. Indian) climate system is more sensitive to smaller variations in cosmic ray intensity than the other.

The purpose of this investigation is to determine the

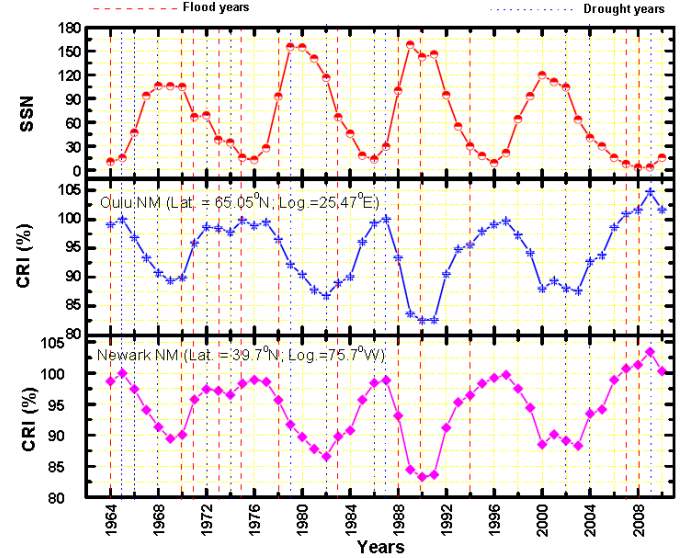


Figure 1: Yearly averaged sunspot number (SSN) and galactic cosmic ray (GCR) intensity variations as observed at Oulu and Newark neutron monitors. Dashed and dotted vertical lines representing drought and flood years respectively

relationship, if any, between the Indian extreme weather (Drought/Flood) and cosmic ray flux variability. We analysed the GCR flux data to evaluate the possible existence of empirical evidence between cosmic ray variability and precipitation in India during monsoon season.

For this study we utilized the GCR fluxes as recorded through the ground based neutron monitors, and perform analysis to look for any possibility of changes in pattern in Indian rainfall, in particular, due to variations in GCR flux. For this purpose we adopt the methods of superposed epoch analysis (Singh and Badruddin, 2006) and regression analysis. We find evidence for a possibility that GCR flux variability may have some influence in suppressing/enhancing the rainfall depending upon the decreasing/increasing nature of GCR variability, in favourable climatic conditions.

2. Analysis

In this work we adopt an approach that assumes that the rainfall changes can occur only with GCR changes if environmental conditions are suitable, and considering that the rate of GCR flux change, and not the mean GCR flux, may be the key (Laken et al., 2010). Usoskin (2011), in a recent review, concluded that it is not the intensity of cosmic rays but its variability that may affect climate.

The GCR flux is provided by neutron monitors, which record neutrons generated chiefly by the primary cosmic ray protons that ionize the lower stratosphere and upper troposphere (Venkatesan and Badruddin, 1990; Bazilevskaya and Svirzhetskaya, 1998). Continuous records of high quality cosmic ray intensity data, measured by neutron monitors located at different latitudes and longitudes on the earth's surface are available from 1964 onwards till date. Reliable and good quality data of monsoon rainfall in India are also available for the

Table 1

All India monthly rainfall data during individual months (<http://www.tropmet.res.in/>), annual, summer monsoon period (June-September; JJAS) and deviation in JJAS (dJJAS) during different years are showing in millimeter for the period (1964-2011). The Average JJAS rainfall amount is 830.1 mm for the period 1964-2011.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	JJAS	dJJAS
1964	1.4	5.7	8.3	24.8	43.7	143.7	313.0	263.6	202.1	73.3	25.7	6.5	1111.8	922.4	92.29
1965	5.5	9.2	14.9	24.3	34.6	110.4	266.8	189.3	142.7	36.2	15.8	22.1	871.8	709.2	-120.91
1966	14.7	5.2	5.1	16.1	52.0	165.8	237.5	198.2	138.4	58.0	61.1	17.8	969.9	739.9	-90.21
1967	9.2	2.7	52.7	22.5	33.3	141.4	292.4	257.3	168.8	42.0	13.1	49.6	1085.0	859.9	29.79
1968	15.0	12.1	20.1	26.9	31.6	136.4	288.6	194.7	134.8	70.3	23.8	7.0	961.3	754.5	-75.61
1969	4.0	2.8	9.5	24.1	55.7	121.0	300.4	238.7	170.9	59.6	43.8	13.9	1044.4	831.0	0.89
1970	16.9	20.7	18.4	24.0	58.0	210.8	222.8	298.9	207.2	76.2	19.4	0.8	1174.1	939.7	109.59
1971	11.4	10.3	9.3	46.0	70.1	219.4	249.3	258.8	159.2	105.2	13.8	10.0	1162.8	886.7	56.59
1972	2.5	13.1	4.8	20.5	44.8	122.6	183.8	217.2	129.2	63.3	30.8	16.0	848.6	652.8	-177.31
1973	4.6	11.9	7.8	19.5	48.8	141.2	278.6	307.4	186.0	125.9	19.6	17.8	1169.1	913.2	83.09
1974	1.9	3.8	13.9	22.2	60.6	105.9	273.6	228.1	140.3	106.5	11.9	4.2	972.9	747.9	-82.21
1975	6.7	9.5	13.7	16.4	40.5	180.1	290.0	264.6	227.8	121.7	25.0	2.7	1198.7	962.5	132.39
1976	4.7	8.1	12.5	29.8	36.7	141.8	288.1	278.6	148.1	31.9	61.6	4.0	1045.9	856.6	26.49
1977	7.0	5.7	8.4	48.9	71.9	188.3	310.6	239.4	144.7	89.3	71.4	8.5	1194.1	883.0	52.89
1978	7.3	21.6	19.5	23.3	50.3	199.6	276.0	273.5	160.1	55.1	44.1	23.0	1153.4	909.2	79.09
1979	14.6	27.2	9.9	15.7	40.5	143.4	225.8	199.0	139.5	46.1	88.3	12.0	962.0	707.7	-122.41
1980	4.4	5.3	16.9	24.5	44.0	215.0	278.2	253.4	136.0	51.8	24.2	17.8	1071.5	882.6	52.49
1981	16.3	7.3	24.7	27.5	58.3	138.6	288.9	226.3	198.3	50.9	29.2	12.8	1079.1	852.1	21.99
1982	16.7	11.0	24.9	36.5	50.4	129.6	216.2	268.4	120.9	48.7	50.4	5.6	979.3	735.1	-95.01
1983	7.3	10.6	12.6	35.3	54.9	137.8	273.7	293.4	250.7	89.9	12.2	26.2	1204.6	955.6	125.49
1984	16.1	26.6	12.2	27.9	39.0	173.8	261.2	259.1	142.4	60.1	13.2	7.8	1039.4	836.5	6.39
1985	17.1	6.9	9.6	23.6	43.9	140.4	253.4	218.5	147.4	113.8	19.3	13.1	1007.0	759.7	-70.41
1986	14.7	28.0	7.5	31.0	43.5	177.6	238.4	213.5	113.4	70.6	38.6	16.9	993.7	742.9	-87.21
1987	11.3	9.3	16.6	21.6	44.8	115.8	206.8	237.0	137.4	86.6	54.1	23.4	964.7	697.0	-133.11
1988	2.5	11.1	18.8	31.9	50.2	156.4	323.2	276.2	205.6	50.1	22.5	10.2	1158.7	961.4	131.29
1989	6.1	3.8	19.1	16.6	42.6	183.5	286.2	231.0	165.8	48.5	14.9	12.1	1030.2	866.5	36.39
1990	5.1	25.6	23.7	29.9	107.7	172.1	263.0	283.3	190.0	100.7	33.4	8.8	1243.3	908.4	78.29
1991	7.9	7.6	12.3	28.2	44.0	179.5	253.8	231.1	120.8	60.4	34.7	12.4	992.7	785.2	-44.91
1992	6.2	9.4	4.8	15.0	44.9	125.5	232.9	269.9	156.5	63.1	48.7	6.9	983.8	784.8	-45.31
1993	3.4	14.5	17.8	25.5	58.7	183.6	280.4	198.5	204.1	90.7	29.0	21.9	1128.1	866.6	36.49
1994	13.1	19.8	13.0	39.2	40.3	217.3	321.5	269.5	144.4	89.6	33.2	3.6	1204.5	952.7	122.59
1995	26.9	12.2	16.5	19.0	84.8	128.5	274.1	232.4	165.2	84.4	38.4	5.8	1088.2	800.2	-29.91
1996	13.1	17.6	13.1	26.2	42.2	188.9	244.0	275.5	150.2	95.3	16.2	15.8	1098.1	858.6	28.49
1997	10.4	4.2	14.6	42.1	42.1	181.1	259.6	263.1	167.6	74.5	59.6	56.5	1175.4	871.4	41.29
1998	14.0	14.9	25.7	27.5	45.1	151.1	256.6	241.9	209.7	116.8	49.2	10.7	1163.2	859.3	29.19
1999	4.1	11.5	3.0	14.8	95.0	176.7	247.2	212.8	185.2	123.3	16.9	3.8	1094.3	821.9	-8.21
2000	5.4	25.2	7.6	29.2	81.0	187.5	249.0	209.4	132.3	42.6	13.4	7.1	989.7	778.2	-51.91
2001	4.8	6.3	11.8	39.9	62.0	230.5	262.5	188.7	111.7	113.0	22.2	6.5	1059.9	793.4	-36.71
2002	11.0	18.5	10.7	28.4	58.1	172.6	117.6	239.1	132.6	65.1	23.7	5.0	882.4	661.9	-168.21
2003	4.7	27.3	18.0	27.5	30.5	163.7	284.7	222.9	178.2	102.0	16.2	12.8	1088.5	849.5	19.39
2004	13.1	3.8	5.7	45.2	82.5	164.0	219.5	232.5	128.7	89.8	16.8	1.8	1003.4	744.7	-85.41
2005	15.7	13.7	24.4	33.3	43.2	147.7	319.3	183.2	206.6	116.3	27.7	10.0	1141.1	856.8	26.69
2006	1.6	3.0	28.1	27.0	77.2	157.9	278.9	270.4	162.7	67.4	35.3	3.2	1112.7	869.9	39.79
2007	0.9	35.2	12.8	31.5	47.0	199.5	278.1	247.8	209.6	58.5	18.3	10.5	1149.7	935.0	104.89
2008	11.5	12.8	42.6	24.5	44.3	216.3	245.4	250.6	174.7	57.6	31.9	6.1	1118.3	887.0	56.89
2009	2.4	1.6	8.7	13.0	51.0	78.2	271.1	179.8	138.5	71.8	59.3	11.0	886.4	667.6	-162.51
2010	6.0	5.4	7.9	27.9	55.1	130.5	280.5	246.2	188.4	69.3	69.3	21.1	1107.6	845.6	15.49
2011	2.0	13.6	9.9	32.8	47.8	192.3	231.9	268.4	188.3	37.8	22.2	4.8	1051.8	880.9	50.79
Avg	8.8	12.4	15.1	27.3	52.7	162.2	262.4	241.7	163.8	75.5	32.6	12.7	1067.0	830.1	-0.002

Table 2

Showing the list of drought and flood years classified based on the deviation in JJAS rainfall amount along with corresponding deviation.

Deficient rainfall (drought) years		Heavy rainfall (flood) years	
Years	Deviation (mm)	Years	Deviation (mm)
1965	-120.91	1964	92.29
1966	-90.21	1970	109.59
1968	-75.61	1971	56.59
1972	-177.31	1973	83.09
1974	-82.21	1975	132.39
1979	-122.41	1978	79.09
1982	-95.01	1983	125.49
1986	-87.21	1988	131.29
1987	-133.11	1990	78.29
2002	-168.21	1994	122.59
2004	-85.41	2007	104.89
2009	-162.51	2008	56.89

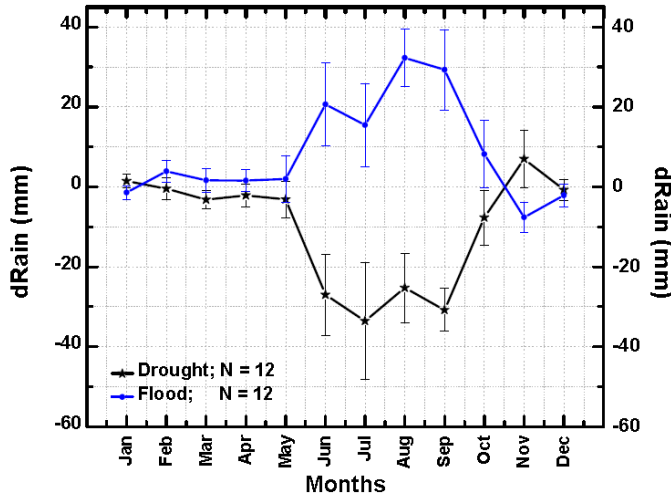


Figure 2: Deviation of monthly rainfall during superposed drought and flood years from superposed average rainfall of 48 years (1964-2011).

period 1964 - 2011 (see Table 1) and many more years before that, at Indian Institute of Tropical Metrology, Pune (India) website (<http://www.tropmet.res.in/>). For this work, we have considered the 48-year period (1964 - 2011) for which both the GCR intensity and Indian Summer Monsoon Rainfall (ISMR) data are available.

3. Results

A variation of $\sim 15\text{--}20\%$ in yearly mean GCR flux over a period of one solar cycle in anti-phase with the ~ 11 -year sunspot polar activity cycle is a well-observed known phenomena (see Fig. 1). A number of studies have utilized this change in GCR intensity over solar cycles to suggest (or refute) a possible connection between cosmic rays and climate (clouds, rainfall, temperature etc.). However, significant changes/fluctuations in GCR intensity are observed when the data is averaged over monthly and daily time resolutions. At times, with these time resolutions, the GCR flux is observed to increase/decrease by a

large amount (a few percent) during some months in the same year and during several days in the same month.

The purpose of this paper to search the influence, if any, of GCR flux change on the summer monsoon rainfall in India, at regional and seasonal or even shorter time scales.

For this purpose out of 48 years from 1964 - 2011 (see Table 1) we first identify \sim one-fourth (12) years with lowest rainfall in four Indian summer monsoon months (June-September) (see Table 2). We call them deficient rainfall ('drought') years and the same number of years (12) with the highest rainfall in summer monsoon months (see Table 2). We call them heavy rainfall ('flood') years. In Fig. 2, the deviation of monthly precipitation during superposed drought and flood years from superposed average precipitation of 48 years (1964-2011) is shown.

In Fig. 1, we have plotted yearly average GCR intensity as observed by neutron monitors located at two different latitudes and longitudes (see Table 3), namely Oulu (<http://cosmicrays oulu.fi/>) and Newark (<http://neutronm.bartol.udel.edu/>). Unfortunately, there is no neutron monitor located in India whose data for the period 1964 - 2011 can be utilized for this analysis. However, the time variation shown in Fig. 1 at two locations on the earth is similar in nature globally with different amplitudes at different latitudes. That is, the nature of GCR variations observed at globally distributed monitors are similar, only differing in amplitudes. However, there are some suggestions (e.g. Eroshenko et al., 2010) that the rainfall and the humidity influence the incoming particle flux around the detector; moisture around the detector lowers both the neutrons incident to the surface and albedo neutrons.

In Fig. 1, the 'drought' and 'flood' years are indicated by dashed and dotted vertical lines respectively. From Fig. 1 we see that in India droughts/floods can occur at any level of mean GCR flux, minimum/maximum or intermediate level. In other words, these floods/droughts can occur at maximum/minimum/increasing/decreasing phases of the solar activity cycle. Thus if we assume mean GCR flux to be the key, then we can conclude that there is no influence of GCR flux on the Indian monsoon rainfall of inter-annual scale. Next, we proceed to search for any possible influence of GCR flux variability on Indian monsoon rainfall during the same period, assuming that it is more likely that the rainfall changes occur only with GCR flux changes if environmental conditions are suitable, and that not the mean GCR flux, but its variability may affect the rainfall amount/climate (see Laken et al., 2010; Usoskin, 2011).

Table 3

Latitude, Longitude and cutoff rigidity of selected cosmic ray stations.

Stations	Latitude	Longitude	Cutoff rigidity
Oulu NM	65.05°N	25.47°E	0.81GV
Kiel NM	54.34°N	10.12°E	2.36GV
Newark NM	39.70°N	75.70°W	2.09GV

The cosmic ray count rate has solar cycle dependence, so

we normalized the count rate before performing the superposed epoch analysis. Each year's data is normalized to the yearly average for that year, then the data is converted to percentage, which in turn allows for a direct comparison of the different data (i.e. GCR intensity, Sunspot number, 10.7 cm solar radio flux, Total Solar Irradiance). First, we have calculated the yearly average for individual years, then each month's data is converted into percentage by taking yearly average as reference. Monthly resolution cosmic ray count rate of Oulu NM during drought and flood years, mean count rate of individual months with standard deviation (σ) and standard error of mean ($SEM = \frac{\sigma}{\sqrt{n}}$) of both before and after normalization are tabulated in Tables 4a and 4b.

We then perform the superposed epoch analysis to study the rate of GCR flux variability during ISMR months (June-September) averaged over 12 drought years and 12 flood years separately. For this purpose we have utilized the normalized GCR intensity data of three neutron monitors located at different positions on the Earth, namely Oulu (Finland), Kiel (Germany) and Newark (USA) (see Table 3). These three location data have been analysed to show that the nature of variation is globally similar, only differing in amplitudes.

In Fig. 3(a) we have plotted the superposed epoch results of monthly averaged normalized GCR intensity data for deficient rainfall years as observed by Oulu neutron monitor count rate. We see that GCR intensity is decreasing during ISMR (June-September) period (shaded). The rate of decrease has been calculated by fitting a linear curve (see Table 5), taking the pre-monsoon (May) value as a reference. The best-fit result shows that the GCR count rate decreases (negative slope) with linear correlation coefficient $R = -0.95$ (see Table 5 and Fig. 3).

As the GCR intensity may fluctuate to a large extent on a day-to-day basis, we have done the superposed epoch analysis of the daily normalized GCR count rate, as observed by the Oulu neutron monitor, for the same 12 deficient rainfall years. The result of this analysis is plotted in Fig. 4(a) and tabulated in Table 5. We see a continuously decreasing GCR intensity during the summer monsoon period. We did a linear regression to this averaged data considering the pre monsoon (May) data as the reference. The best-fit line with negative slope ($R = -0.90$) is also shown (see Table 5 and Fig. 4). In both monthly and daily cases, we note that the regression line is steeper than it would be if the regression line is obtained using the entire year.

To show that such a variation is not confined to one location but its nature is global, we did a similar superposed epoch analysis and best fit linear regression, as earlier, for two more neutron monitor stations data namely Kiel and Newark using monthly average GCR count rate as well as daily count rate (see Table 5). We see a similar decreasing trend at these locations also. Thus, we can infer that the trends of rate of change in GCR flux will be similar in nature at Indian locations also.

Next, we consider the same number (12) of heavy rainfall years and did a similar superposed epoch analysis of GCR count rate (both monthly and daily) data for the same three neutron monitors. We also did a linear regression of these data for the ISMR period taking pre-monsoon (May) value as a reference.

We find that GCR flux is increasing during ISMR periods. The best-fitted linear curves with positive slope and correlation coefficients are clearly evident on all three-neutron monitor stations and at both time resolutions (see Figs. 3, 4 and Table 5). The linear regression shows a line with positive slope [see Figs. 3(e) and 4(e)], and from these figures it is clear that the slope will be less rapid if a regression line is drawn for the entire year.

In addition to cosmic rays, we extended our analysis to solar activity parameters, such as sunspot number (SSN) and 10.7 cm solar radio flux (<http://omniweb.gsfc.nasa.gov/>). The SSN is the oldest directly observed solar activity on the photosphere and a very useful indicator of solar activity. The 10.7 cm solar radio flux is an indicator of activity in the upper chromosphere and lower corona. We also considered Total Solar Irradiance (TSI) data; however, this data is available only from 1979 onwards (<http://www.ngdc.noaa.gov/>; <http://lasp.colorado.edu/home/sorce/data/tsi-data/>).

We analysed both monthly and daily resolution data of solar parameters SSN, 10.7 cm solar radio flux and TSI for drought and flood years. We carried out superposed epoch analysis after normalizing the data as done for GCR count rate. Superposed epoch results of monthly averaged normalized SSN, 10.7 cm solar radio flux and TSI are plotted in Fig. 3 for both drought years [Fig. 3(b-d)] and flood years [Fig. 3(f-h)]. The rate of change has been calculated by fitting a linear curve, taking the pre-monsoon (May) value as a reference. The best-fit results with linear correlation coefficient are also shown (see Fig. 3 and Table 5). We have also done the superposed epoch analysis of the daily normalized solar parameters data, for the same 12 drought ((b-d) of Fig. 4) and flood ((f-h) of Fig. 4) rainfall years. The rate of change has been calculated by fitting a linear curve to the data. The best-fit results with linear correlation coefficient are tabulated in Table 5. We can see the difference in nature of variability (slopes) in GCR flux and solar parameters (SSN, 10.7 cm solar radio flux, TSI), errors in slopes and correlation coefficients (R) during drought and flood periods, favouring GCR flux-rainfall relationship. Noticeable difference seen in GCR variability is not so clear in solar parameters considered here. However, it is possible that restricting the correlation analysis to ISMR months only reduces the apparent dependence on solar indices such as F10.7 and SSN. But the anti-correlation between GCR flux and SSN and F10.7 becomes clearer if the analysis interval is extended to whole year.

We observe that on an average, the GCR flux is decreasing during ISMR months (June-September) with deficient monsoon rainfall (drought) in India. On the other hand, GCR flux is increasing during ISMR period with heavy rainfall (flood) in India. As regards the change in temperature with rainfall changes, we find that there is a strong inverse relation between the rainfall and temperature (see Fig. 5), at least during ISMR period.

In the view of the results shown in Figs. 3 and 4, there is urgent need to quantify the extent of influence, and to identify the physical mechanism(s), responsible for influencing the Indian monsoon rainfall through the cosmic ray flux variability. Although, we found definite trends i.e., on the average, heavy rainfall (floods) in India occurs during ISMR period when GCR flux is increasing in the same season, and GCR flux is decreas-

Table 4a

Monthly cosmic ray count rate of Oulu NM (<http://cosmicrays.oulu.fi/>) for drought years along with superposed average, standard deviation (σ) and standard error in mean (SEM) before normalization.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1965	6505	6466	6532	6592	6619	6512	6472	6453	6470	6508	6558	6507
1966	6423	6376	6410	6396	6434	6345	6304	6277	6040	6162	6220	6155
1968	5953	5879	5912	6049	5984	5905	5924	5942	5893	5801	5623	5654
1972	6227	6130	6391	6445	6410	6269	6356	6092	6348	6353	6148	6354
1974	6453	6480	6417	6383	6281	6213	6094	6194	6149	6155	6192	6303
1979	6179	6152	6077	5953	5997	5857	5863	5726	5780	5882	5889	6000
1982	5830	5629	5815	5861	5916	5629	5415	5387	5258	5400	5463	5366
1986	6276	6160	6261	6389	6408	6417	6424	6432	6451	6483	6391	6497
1987	6581	6603	6612	6591	6549	6440	6393	6337	6287	6291	6245	6254
2002	5735	5910	5845	5848	5859	5908	5808	5684	5780	5825	5728	5756
2004	5755	5922	6042	6105	6166	6163	6077	6114	6153	6296	6135	6182
2009	6713	6736	6781	6820	6825	6814	6805	6803	6818	6838	6842	7125
Average	6219.17	6203.58	6257.92	6286	6287.33	6206	6161.25	6120.08	6118.92	6166.17	6119.5	6179.42
σ	334.36	334.25	317.08	316.44	306.16	333.29	373.02	389.30	408.24	387.72	393.59	457.60
SEM	96.52	96.49	91.53	91.35	88.38	96.21	107.68	112.38	117.85	111.92	113.62	132.10

Table 4a Continues; Cosmic ray count data, average, σ and SEM after normalization.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1965	99.83	99.23	100.24	101.16	101.58	99.94	99.32	99.03	99.29	99.87	100.64	99.86
1966	102.03	101.28	101.82	101.60	102.21	100.79	100.14	99.71	95.95	97.88	98.81	97.77
1968	101.30	100.04	100.60	102.93	101.83	100.48	100.81	101.11	100.28	98.71	95.68	96.21
1972	98.94	97.40	101.55	102.41	101.85	99.61	100.99	96.80	100.86	100.94	97.69	100.96
1974	102.82	103.25	102.24	101.70	100.08	98.99	97.10	98.69	97.97	98.07	98.66	100.43
1979	103.91	103.46	102.20	100.11	100.85	98.50	98.60	96.30	97.20	98.92	99.04	100.90
1982	104.47	100.86	104.20	105.02	106.01	100.86	97.03	96.53	94.22	96.76	97.89	96.15
1986	98.33	96.52	98.10	100.10	100.40	100.54	100.65	100.78	101.07	101.58	100.13	101.80
1987	102.32	102.66	102.80	102.47	101.82	100.13	99.39	98.52	97.75	97.81	97.09	97.23
2002	98.76	101.77	100.65	100.70	100.89	101.74	100.01	97.88	99.53	100.31	98.64	99.12
2004	94.46	97.20	99.17	100.21	101.21	101.16	99.75	100.35	100.99	103.34	100.70	101.47
2009	98.33	98.67	99.33	99.90	99.98	99.81	99.68	99.65	99.87	100.17	100.22	104.37
Average	100.46	100.2	101.08	101.53	101.56	100.21	99.46	98.78	98.75	99.53	98.77	99.69
σ	2.87	2.41	1.73	1.51	1.58	0.91	1.30	1.64	2.17	1.87	1.52	2.48
SEM	0.83	0.69	0.50	0.44	0.46	0.26	0.38	0.47	0.63	0.54	0.44	0.72

Table 4b

Monthly cosmic ray count rate of Oulu NM (<http://cosmicrays.oulu.fi/>) for flood years along with superposed average, standard deviation (σ) and standard error in mean (SEM) before normalization.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	--	--	--	6414	6424	6428	6461	6467	6491	6475	6468	6512
1970	5791	5789	5794	5803	5841	5698	5689	5781	5869	5910	5794	5939
1971	5909	6003	5955	6089	6132	6254	6265	6319	6323	6386	6348	6294
1973	6365	6333	6308	6197	6126	6262	6313	6360	6472	6446	6475	6475
1975	6318	6374	6389	6429	6438	6462	6447	6405	6427	6420	6356	6429
1978	6343	6311	6298	6185	6052	6152	6159	6309	6317	6221	6262	6270
1983	5512	5644	5762	5768	5601	5707	5818	5823	5463	5894	5923	5925
1988	6081	6143	6168	6136	6152	6127	6017	6021	6015	5992	5969	5812
1990	5419	5441	5373	5266	5246	5235	5381	5352	5453	5551	5630	5644
1994	6299	6195	6201	6181	6248	6254	6287	6339	6370	6336	6328	6315
2007	6578	6551	6588	6650	6651	6655	6645	6637	6652	6656	6647	6650
2008	6592	6576	6577	6587	6578	6582	6598	6636	6658	6678	6704	6702
Average	6109.73	6123.64	6128.46	6142.08	6124.08	6151.33	6173.33	6204.08	6209.17	6247.08	6242	6247.25
σ	403.45	368.37	373.50	386.58	406.58	414.37	383.12	385.41	418.43	342.46	339.30	341.59
SEM	116.47	106.34	107.82	111.60	117.37	119.62	110.60	111.26	120.79	98.86	97.95	98.61

Table 4b Continues; Cosmic ray count data, average, σ and SEM after normalization.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	--	--	--	99.29	99.44	99.50	100.02	100.11	100.48	100.23	100.12	100.80
1970	99.70	99.67	99.76	99.91	100.57	98.10	97.95	99.53	101.05	101.75	99.76	102.25
1971	95.46	96.98	96.21	98.37	99.07	101.04	101.22	102.09	102.15	103.17	102.56	101.68
1973	100.33	99.82	99.43	97.68	96.56	98.70	99.51	100.25	102.01	101.60	102.06	102.06
1975	98.60	99.47	99.71	100.33	100.47	100.85	100.61	99.96	100.30	100.19	99.19	100.33
1978	101.65	101.14	100.93	99.12	96.99	98.59	98.70	101.11	101.24	99.70	100.35	100.48
1983	96.08	98.38	100.44	100.55	97.64	99.48	101.42	101.50	95.23	102.74	103.25	103.28
1988	100.47	101.49	101.90	101.38	101.64	101.23	99.41	99.48	99.38	99.00	98.62	96.02
1990	100.06	100.46	99.21	97.23	96.86	96.66	99.36	98.82	100.68	102.49	103.95	104.21
1994	100.31	98.66	98.75	98.43	99.50	99.60	100.12	100.95	101.44	100.90	100.77	100.57
2007	99.22	98.81	99.37	100.30	100.32	100.38	100.23	100.11	100.33	100.39	100.26	100.30
2008	99.54	99.30	99.32	99.47	99.33	99.39	99.63	100.21	100.54	100.84	101.23	101.20
Average	99.22	99.47	99.55	99.34	99.03	99.46	99.85	100.34	100.40	101.08	101.01	101.10
σ	1.88	1.29	1.43	1.24	1.66	1.33	0.99	0.92	1.80	1.29	1.64	2.02
SEM	0.54	0.37	0.41	0.36	0.48	0.38	0.28	0.27	0.52	0.37	0.47	0.58

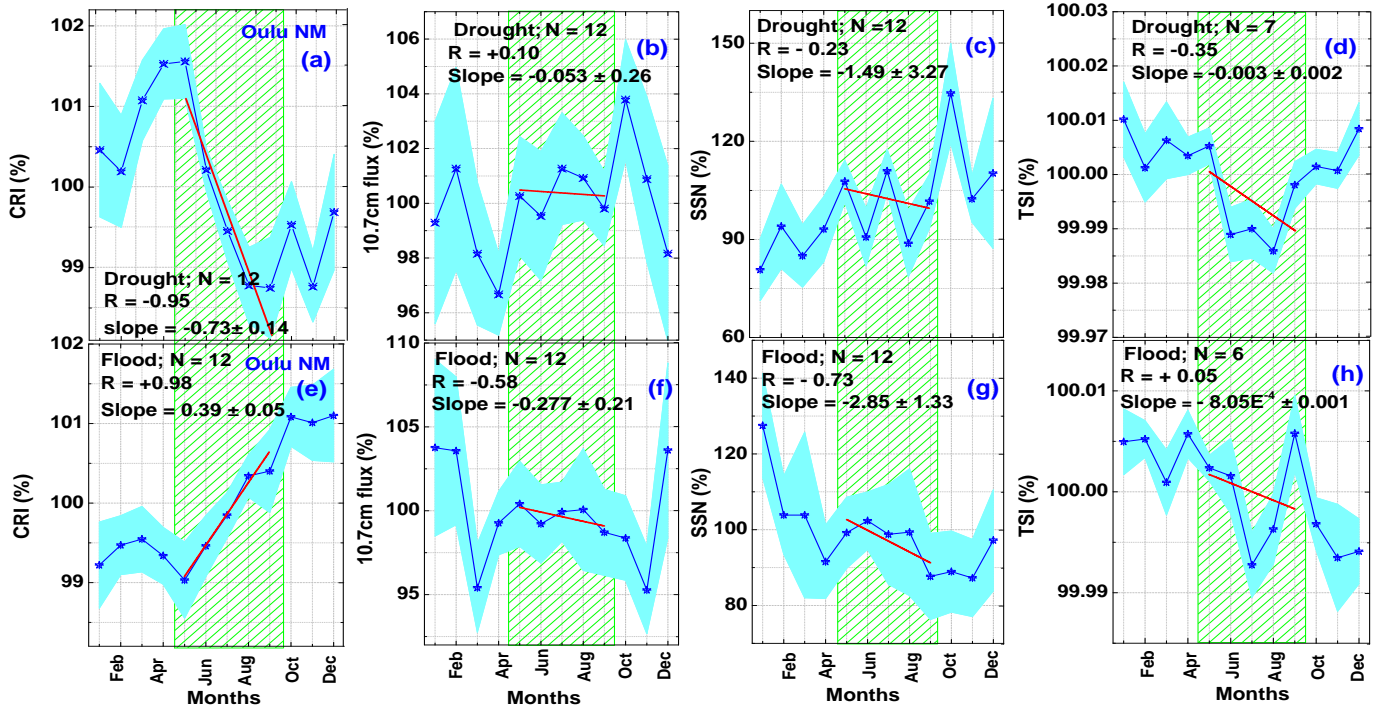


Figure 3: Superposed epoch results of monthly averaged normalized GCR intensity, 10.7cm solar radio flux, SSN and Total solar irradiance along with standard error of mean (color filled around blue line), best-fit linear curve (red straight line) and linear correlation coefficient during ISMR (June-September) period, considering the pre monsoon (May) data as the reference, for deficient rainfall years in upper panel and heavy rainfall years in lower panel.

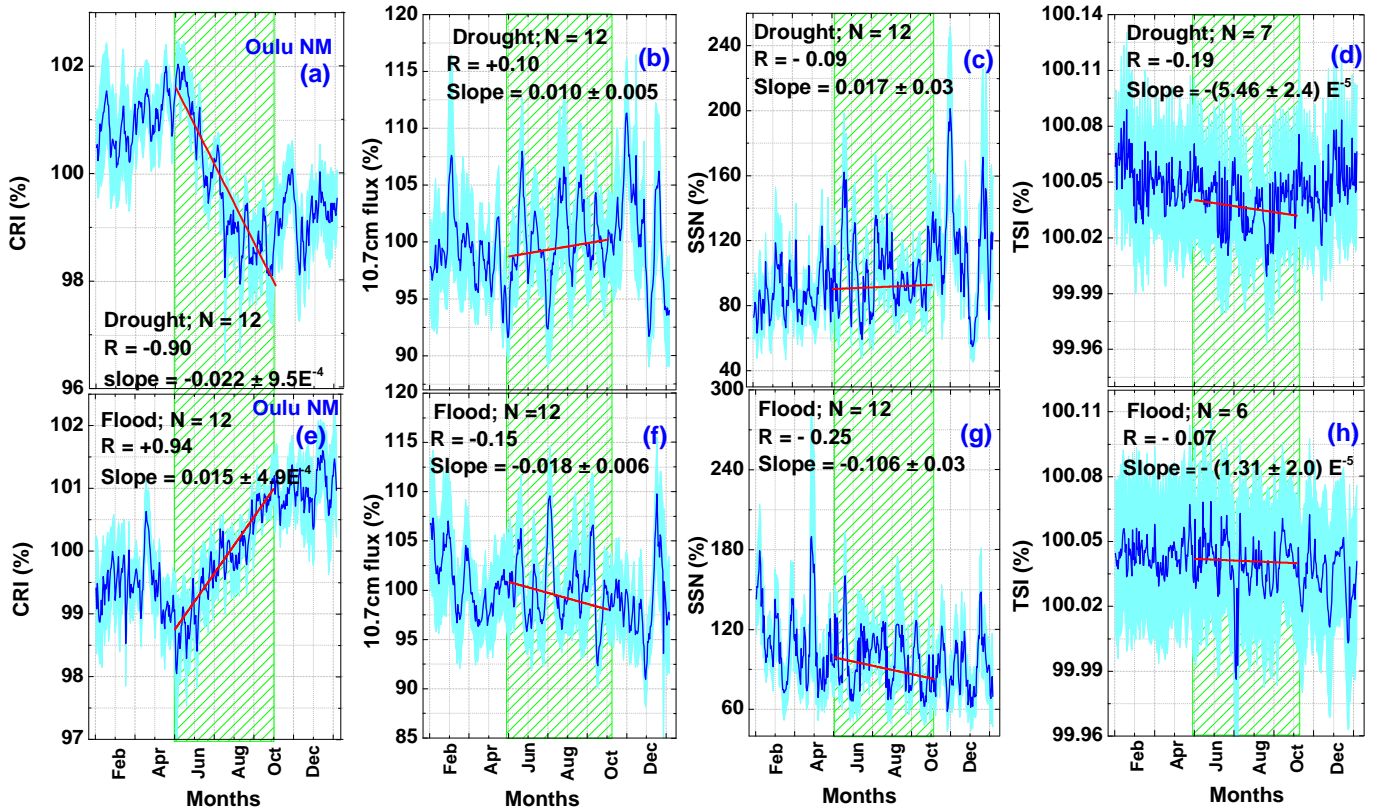


Figure 4: Superposed epoch results of daily averaged normalized GCR intensity, 10.7cm solar radio flux, SSN and Total solar irradiance along with standard error of mean (color filled around blue line), best-fit linear curve (red straight line) and linear correlation coefficient during ISMR (June-September) period, considering the pre monsoon (May) data as the reference, for deficient rainfall years in upper panel and heavy rainfall years in lower panel.

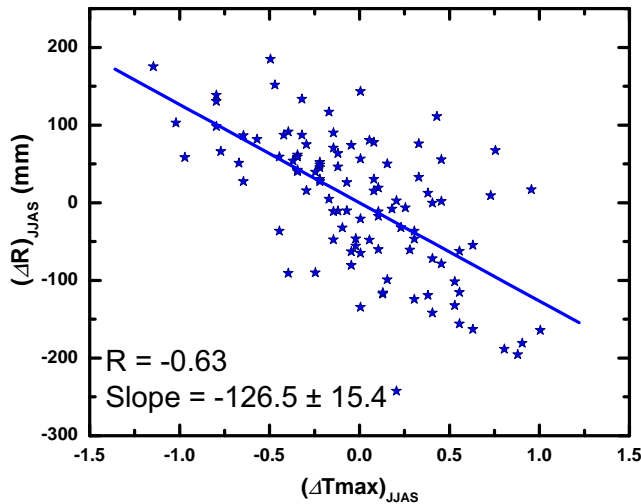


Figure 5: Showing the correlation between deviations from averages in monsoon rainfall [(R)JJAS] and maximum temperature [(Tmax)JJAS] during ISMR months.

ing in ISMR months during deficient rainfall (drought) in Indian Summer Monsoon period. However, a caveat must be added here; that the rainfall changes can occur with GCR changes only if environmental conditions (to be identified) are suitable. This caveat implies that similar trends in rainfall changes with GCR flux changes (i.e., deficient rainfall associated with decreasing GCR flux and heavy rainfall associated with increasing GCR flux) may not be observed at all geographic locations from equator to pole and in all seasons simultaneously, although the nature of GCR flux change is overall similar at almost all locations on the earth only differing in magnitude. Moreover, there may be exceptions in India even during ISMR season due to unsuitable environmental conditions.

As regard the breakdown of the ENSO-ISMR connection after 1988, mentioned earlier, the breakdown may be because the ISMR is less variable. Similarly to ENSO, the GCR flux variability has similar properties on both the quiet interval from 1989 to 2002 and the drought and flood periods before and after this gap. Thus the breakdown in the ISMR-ENSO connection is not necessarily the evidence for the ISMR-GCR hypothesis. The possibility of both the ENSO and GCR variability contributing to ISMR variability in their own way cannot be ruled out at this stage. More efforts and rigorous analyses are required to discriminate between ENSO and GCR as a cause of ISMR variability.

4. Discussions

Most of the studies that attempt to study possible GCR-cloud-climate relationship are focused on longer time scales (millennial, centennial, multidecadal and decadal) (e.g. see reviews by Carslaw et al., 2002; Kirkby, 2007; Singh et al., 2011; Rao, 2011; and references therein). However, on shorter time scales too (inter-annual, seasonal and even smaller) attempts have been made to search for this relationship with conflicting results.

Forbush decreases are sudden decreases ~a few percent in cosmic ray intensity within about a day and recover to its pre-reverse level within a week or so (e.g. see Rao, 1972; Venkatesan and Badruddin, 1990; Kudela, 2009 for reviews on cosmic ray variations at different time scales). These Forbush decreases in cosmic rays are thought to be an important laboratory for testing possible cosmic ray climate connection. Decreases in rainfall in the former Soviet Union have been reported in the days of the Forbush decreases (Stozhkov et al., 1995). However, most of the Eastern Mediterranean stations present higher probabilities for a precipitation episode one day after a Forbush decrease (Mavrakakis and Lykoudis, 2006). Precipitation changes in relation to GCR flux changes in a short time scale have also been studied by Kniveton and Todd (2001).

A recent claim that Forbush decreases affect atmospheric aerosol and cloud (Svensmark et al., 2009) has been challenged by other studies (Kulmala et al., 2009; Laken et al., 2009; Calogovic et al., 2010) who found no connection between cosmic rays, aerosols and clouds. However, a more recent study (Dragic et al., 2011) from an analysis of European region data supports the idea that cosmic rays influence the atmospheric process and climate. Earlier too, the claim of decreased cloudiness detected during Forbush decreases (Pudovkin and Veretenenko, 1995) was not observed by Palle and Butler (2001) even during the same Forbush decreases. Moreover, the underlying physics suggesting for a connection between cosmic rays, aerosols and cloud is still highly speculative (Legras et al., 2010) and empirical evidences for cosmic ray-cloud relation is still inconclusive (Usoskin, 2011).

It was concluded in a review (Kirkby, 2007), based on the available results for longer timescales (millennial, centennial and multi decadal), that increased GCR flux appears to be associated with a cooler climate and a weakening of the monsoon; and a decreased GCR flux is associated with a warmer climate and strengthening of the monsoon. From our observations on a much shorter time scale during monsoon season in India, we observe that a decreasing GCR flux corresponds to decreasing rainfall and increasing GCR flux corresponds to increasing rainfall. Moreover, our preliminary results reported earlier (Badruddin et al., 2006, 2009) show that temperature and rainfall changes show an opposite behaviour, i.e., temperature is enhanced during deficient ISMR periods and it is lower in heavy rainfall ISMR periods.

The observation that the cosmic ray intensity is decreasing during ISMR months in almost all the years which, are deficient in rainfall ('drought' years) may be interpreted to suggest that a GCR-rainfall relation is possible in Indian sub-continent during ISMR periods, at least. Thus, the GCR-rainfall relation should be considered as a potentially important driver of climate variability.

A significant part of precipitation that falls in the tropics is warm rain formed by coalescence of cloud droplets (Kostinski and Shaw, 2005). Formation of cloud droplets requires a water vapour super saturation environment and particles able to act as cloud condensation nuclei. Usually cloud droplets are formed on aerosol particles containing a certain stable fraction. After condensation droplets grow by vapour diffusion

Table 5

Change in CRI and solar parameters against months (May-September) and their correlation coefficients (*R*) during drought and flood years for monthly resolution data.

	CRI stations						Solar parameters					
	Oulu		Kiel		Newark		10.7cm flux		SSN		TSI	
	Slope	R	Slope	R	Slope	R	Slope	R	Slope	R	Slope	R
Drought	-0.73 ± 0.14	-0.95	-0.70 ± 0.12	-0.96	-0.70 ± 0.13	-0.95	-0.053 ± 0.26	+0.10	-1.49 ± 3.27	-0.23	-0.003 ± 0.002	-0.35
Flood	0.39 ± 0.05	+0.98	0.45 ± 0.03	+0.992	0.42 ± 0.03	+0.994	-0.277 ± 0.21	-0.58	-2.85 ± 1.33	-0.73	-8.05E ⁻⁴ ± 0.001	+0.05

Table 5 Continues for daily resolution data.

	CRI stations						Solar parameters					
	Oulu		Kiel		Newark		10.7cm flux		SSN		TSI	
	Slope	R	Slope	R	Slope	R	Slope	R	Slope	R	Slope	R
Drought	-0.022 ± 9.5E ⁻⁴	-0.90	-0.023 ± 9.2E ⁻⁴	-0.90	-0.022 ± 9.8E ⁻⁴	-0.89	0.010 ± 0.005	+0.10	0.017 ± 0.03	-0.09	-(5.46 ± 2.4)E ⁻⁵	-0.19
Flood	0.015 ± 4.9E ⁻⁴	+0.94	0.015 ± 6.7E ⁻⁴	+0.88	0.014 ± 5.1E ⁻⁴	+0.91	-0.018 ± 0.006	-0.15	-0.106 ± 0.03	-0.25	-(1.31 ± 2.0)E ⁻⁵	-0.07

and droplet-droplet collision (coalescence), the latter providing more rapid growth as droplet size increases (Harrison and Ambaum, 2009). Electrical effects play an important role in cloud microphysics. Both condensation and coalescence can be influenced by the charge (Pruppacher and Klett, 1997; Tinsley, 2008). Early laboratory studies found that raindrops (of around 0.5mm diameter) are about factor 100 more efficient at collecting aerosols when they are charged rather than neutral (Barlow and Latham, 1983). Grover and Beard (1975) calculated collision efficiencies and found a significant increase in collision efficiency when the droplets were loaded with a charge of the magnitude typical of thunderstorm clouds. Khain et al. (2004) from their simulation results have shown that the injection of just a small fraction of charged particles rapidly triggered the collision process and lead to raindrop formation a few minutes after the injection, thus seeding with charged particles may be a very efficient tool for rain enhancement, they suggested. The collision efficiencies highly depend on droplet charge and size. The collision efficiency is much enhanced in the case of a charged droplet collisions than in case of neutral droplet collisions. More specifically, they found that the collision efficiency between charged and neutral droplets, as well as between droplet charges of opposite polarity, is many orders higher than in the case of gravity-induced collisions. Thus, efficient collision takes place between cloud droplets and coalescence to large droplet is enhanced by electrical forces between charged droplets. This significantly increases the rate of raindrop formation (Khain et al., 2004). Another potential mechanism may operate through electrostatic image forces. Because of electrostatic image forces, electrical forces between charged droplets are always attractive at small separations whatever the relative polarities of the colliding particles (Tinsley, 2008). In this case, the attraction between droplets may lead to droplet size increase. As the droplet size increases, the droplet-droplet collision (coalescence) will lead to more rapid growth, leading to enhanced rate of raindrop formation, as suggested by Harrison and Ambaum (2009). This mechanism appears more likely as the rate of change of GCR flux and not the amount of GCR flux is considered to be the key factor. However, more simu-

lations and experiments need to be performed to demonstrate clearly how the increasing GCR flux corresponds to increasing rainfall and vice versa.

Thus it is expected that in proper atmospheric/environmental conditions (e.g. air humidity, aerosols, temperature, cloud type etc.) increasing GCR flux will increase coalescence efficiency that will lead to bigger rain droplets while decreasing GCR flux will decrease the coalescence efficiency and will suppress the droplet growth. During decreasing flux of cosmic rays, levitation/dispersion of low clouds due to electrical effects (Levin and Ziv, 1974) may also play some role in such a way that it disperses the low cloud amount in proper climatic conditions. We suspect that in suitable environmental conditions, charge particle (cosmic ray) flux rate change modulates the droplet collision and coalescence efficiency and affects the rainfall to certain extent.

Rain formation is a function of different parameters of macro- and micro-physics. The important parameter for the microphysics is the ambient temperature where clouds reside and formation of raindrops occurs due to process of spontaneous coalescence and accretion (Rogers and Yau, 1989). Although the initiation of raindrop coalescence remain an unsolved problem in cloud physics (Kostinski and Shaw, 2005), we suspect that charge induced cloud microphysics, for example, accelerating/decelerating coalescence to larger raindrops (Harrison and Ambaum, 2009) is the likely effect that plays some role in affecting the rainfall variability in India during Indian Summer Monsoon Season, at least, depending on the increasing/decreasing rate of change of charge particle (cosmic ray) flux in the corresponding period, under suitable environmental conditions (e.g. cloud type, temperature, pressure etc.).

Monsoon rainfall variability is connected with global precipitation (Hulme et al., 1998). There is a strong inverse relationship between the monsoon variability and tropical belt temperature (see Dugam and Kakade, 1999; Badruddin et al., 2006, 2009). Considering that change in monsoon rainfall variability is also consistent with the change in global mean precipitation (Hulme et al., 1998) and precipitation/rainfall is inversely related to temperature (see Fig. 8), we suspect that the monsoon

rainfall variability may have some influence on the changes in global temperature also. Thus, it should be clarified whether monsoon/rainfall variability plays any role in global warming or its effects are only local. It has been suggested (Ban-Weiss et al., 2011) that evaporated water helps in cooling earth as a whole and not just the local area of evaporation. On the other hand, reduction in evaporated water is likely to contribute to global warming significantly.

The possible influence of GCR on clouds is a controversial issue. It appears that GCR flux variability plays an important role in influencing the ISMR in this season, at least. It is likely, as we suspect, that the physical state of the cloud droplets may play a significant role. Local physical (cloud type, temperature, humidity etc.) and chemical conditions may play a major role (Engelhoff et al., 2011; Duplissy et al., 2010; Kirkby et al., 2011) in deciding the extent of the influence. Physics of liquid and ice cloud may differ (Geirns and Ponater, 1999). Low clouds generally consist of liquid water droplets (Marsh and Svensmark, 2000). It has been suggested that low cloud liquid droplets over the tropics are more sensitive to cosmic ray variability (Palle and Butler, 2000). It is suggested that such studies (i.e., effects of GCR flux variability on rainfall variability) on regional hydrological regions have to be studied in more detail. It is also suggested that proper environmental condition in which the influence of GCR flux variability of rainfall is more significant, needs to be identified.

Although amount of cloud may be dependent on GCR flux, in our hypothesis, we do not consider a direct relationship between the GCR flux and amount of cloud cover as the key; it is still controversial. We propose an alternate scenario, although speculative, in which the cosmic ray variability influences the rainfall from clouds that are formed in proper environmental conditions. We propose that increasing/decreasing GCR flux influences the rainfall which later results in enhanced/reduced evaporation. This change in evaporation from the Earth surface influences the low cloud amount which in turn alters the planetary albedo and consequently there is change in the temperature. However, such influence is only regional or has global effect needs to be verified. Therefore, more research is needed to understand the relationship among variability in GCR, ISMR, surface evaporation, low cloud, planetary albedo and temperature. Also model studies are needed to understand the extent to which such variability influences the regional and global rainfall and temperature.

5. Conclusions

We find that the decreasing cosmic ray flux does play a role in such a way that the rainfall over this region of the globe (India), at least, is reduced when cosmic ray flux is decreasing. We speculate that the hypothesis, proposed here, on the basis of Indian climate data, can be extended to whole tropical and subtropical belt, and that it may contribute to global temperature in some way.

In conclusion, a GCR-ISMR link seems plausible and the GCR-rainfall relation should be considered as a potentially important driver of climate variability. However, further studies

are required to improve our understanding of the link between cosmic rays and summer monsoon climate over India. It is also required to fully investigate the contributions of possible mechanisms, discussed here, to the variability in precipitation. Further, once our hypothesis is confirmed, there is an urgent need to identify the local physical and chemical conditions conducive for significant effect of GCR flux variability in influencing the rainfall/precipitation.

We suggest the following scenario, although speculative, for possible relationship between GCR flux-rainfall-temperature.

1. Increasing GCR flux \rightarrow increasing rainfall \rightarrow enhanced surface evaporation \rightarrow increased low cloud \rightarrow more scattering of solar radiation back to space (more planetary albedo) \rightarrow lower temperature.
2. Decreasing GCR flux \rightarrow decreasing rainfall \rightarrow decreased surface evaporation \rightarrow reduced low cloud \rightarrow less scattering of solar radiation back to space (less planetary albedo) \rightarrow higher temperature.

Acknowledgements

We thank Station Manager Ilya Usoskin and Sodankylä Geophysical Observatory for the online availability of Oulu neutron monitor data, The National Science Foundation (supporting Bartol Research Institute neutron monitors) and Principle Investigator John W. Bieber for the online availability of Newark neutron monitor data and Christian T. Steigies and Extraterrestrial Physics Department of University of Kiel for the online availability of Kiel neutron monitor data. Availability of Indian climate data through Indian Institute of Tropical Meteorology Pune's website and its use is gratefully acknowledged with thanks. We also acknowledge the use of SSN and 10.7 cm solar radio flux data available through the NASA/GSFC OMNI Web interface, Total Solar Irradiance data through National Geophysical Data Center website and SORCE homepage. The authors also thank the Editor and Referees, whose comments and suggestions helped us to improve the paper.

References

- Agnihotri, R., Dutta, K., Bhushan, R., Somayajulu, B. L. K., 2002. Evidence for solar forcing on the Indian monsoon during the last millennium. *Earth Planet. Sci. Lett.* 198, 521-527.
- Ashok, K., Guan, Z., Yamagata, T., 2001. Impact of Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys. Res. Lett.* 28, 4499-4502.
- Badruddin, Singh, Y. P., Singh, M., 2006. Does solar variability affect Indian (Tropical) weather and climate?: An assessment. In: Gopalswamy, N., Bhattacharya, A. (Eds.), *Solar influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects (Proc. ILWS Workshop)*. Quest Publications, 444-447.
- Badruddin, Aslam, O. P. M., Singh, M., 2009. Influence of solar and cosmic-ray variability on climate. *Proc. 31st Int. Cosmic Ray Conf. Lodz, SH 3.4*, 1-3.
- Ban-Weiss, G. A., Bala, Govindaswamy, Cao, L., Pongratz, J., Caldeira, K., 2011. Climate forcing and response to idealized changes in surface latent and sensible heat. *Environ. Res. Lett.* 6, 034032.
- Bazilevskaya, G. A., Svirzhetskaya, A. K., 1998. On the stratospheric measurements of cosmic rays. *Space Sci. Rev.* 85, 431521.

- Barlow, A. K., Latham, J., 1983. A laboratory study of the scavenging of sub-micron aerosol by charged raindrops. Royal Meteorological Society, Quart. J. 109, 763-770.
- Bhalme, H. N., Reddy, R. S., Mooley, D. A., Ramana Murty, Bh. V., 1981. Solar activity and Indian weather/climate. Earth Planet. Sci. 90, 245-262.
- Bhattacharya, S., Narasimha, R., 2005. Possible association between Indian monsoon rainfall and solar activity. Geophys. Res. Lett. 32, L05813.
- Calogovic, J., Albert, C., Arnold, F., Beer, J., Desorgher, L., Flueckiger, E. O., 2010. Sudden cosmic ray decreases: No change of global cloud cover. Geophys. Res. Lett. 37, L03802.
- Carslaw, K. S., Harrison, R. G., Kirkby, J., 2002. Cosmic Rays, Clouds, and Climate. Science, 298, 1732-1737.
- Dragi, A., Anin, I., Banjanac, R., Udovii, V., Jokovi, D., Maleti, D., Puzovi, J., 2011. Forbush decreases-clouds relation in the neutron monitor era. Astrophys. Space Sci. Trans. 7, 315-318.
- Dugam, S. S., Kakade, S. B., 1999. Global temperature and monsoon activity. Proc. Indian Acad. Sci. (Earth and Planet. Sci.), 108, 305-307.
- Duplissy, J., Enghoff, M. B., Aplin, K. L., Arnold, F., et al., 2010. Results from the CERN pilot CLOUD experiment. Atmos. Chem. Phys. 10, 1635-1647.
- Enghoff, M. B., Pedersen, J. O. P., Uggerhoj, U. I., Paling, S. M., Svensmark, H., 2011. Aerosol nucleation induced by a high energy particle beam. Geophys. Res. Lett. 38, L09805.
- Eroshenko, E., Velinov, P., Belov, A., Yanke, V., Pletnikov, E., Tassev, Y., Mischev, A., Mateev, L., 2010. Relationships between neutron fluxes and rain flows. Adv. Space Res. 46, 637-641.
- Gadgil, S., Vinayachandran, P. N., Francis, P. A., Gadgil, S., 2004. Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. Geophys. Res. Lett. 31, L12213.
- Gierens, K., Ponater, M., 1999. Comment on 'Variation of cosmic ray flux and global cloud coverage - a missing link in solar-climate relationships' by H. Svensmark and E. Friis-Christensen (1997). J. Atmos. Sol. Terr. Phys. 61, 795-797.
- Grover, S. N., Beard, K. V., 1975. A numerical determination of the efficiency with which electrically charged cloud drops and small raindrops collide with electrically charged spherical particles of various densities. J. Atmos. Sci. 32, 2156-2165.
- Gupta, A. K., Das, M., Anderson, D. M., 2005. Solar influence on the Indian summer monsoon during the Holocene. Geophys. Res. Lett. 32, L17703.
- Harrison, R. G., Ambaum, M. H. P., 2009. Observed atmospheric electricity effect on clouds. Environ. Res. Lett. 4, 014003.
- Hiremath, K. M., Mandi, P. I., 2004. Influence of the solar activity on the Indian Monsoon rainfall. New Astron. 9, 651-662.
- Hong, Y.T., Wang, Z. G., Jiang, H. B., Lin, Q. H., Hong, B., Zhu, Y. X., Wang, Y., Xu, L. S., Leng, X. T., Li, H. D., 2001. A 6000-year record of changes in drought and precipitation in northeastern China based on a 13C time series from peat cellulose. Earth Planet. Sci. Lett. 185, 111-119.
- Hulme, M., Timothy O. J., Timothy J. C., 1998. Precipitation sensitivity to global warming: Comparison of observations with HadCM2 simulations. Geophys. Res. Lett. 25, 3379-3382.
- Jagannathan, P., Bhalme, H. N., 1973. Changes in the Pattern of Distribution of Southwest Monsoon Rainfall Over India Associated With Sunspots. Mon. Weather Rev. 101, 691-700.
- Khare, N., Nigam, R., 2006. Can the possibility of some linkage of monsoonal precipitation with solar variability be ignored? Indications from foraminiferal proxy records. Curr. Sci., 90, 1685-1688.
- Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A., Phillips, V., 2004. Simulation of Effects of Atmospheric Aerosols on Deep Turbulent Convective Clouds Using a Spectral Microphysics Mixed-Phase Cumulus Cloud Model. Part I: Model Description and Possible Applications. J. Atmos. Sci. 61, 2963-2982.
- Kirkby, J., 2007. Cosmic rays and climate. Surv. Geophys. 28, 333-375.
- Kirkby, J., Curtius, J., Almeida, J., Dunne, E., et al., 2011. Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. Nature, 476, 429-433.
- Kniveton, D. R., Todd, M. C., 2001. On the relationship of cosmic ray flux and precipitation. Geophys. Res. Lett. 28, 1527-1530.
- Kostinski, A. B., Shaw, R. A., 2005. Fluctuations and Luck in Droplet Growth by Coalescence. Bulletin of the American Meteorological Society, 86, 235-244.
- Kripalani, R. H., Kulkarni, A., 1997. Climate impact of El Nio/La Nia on the Indian monsoon: A new perspective. Weather, 52, 39-46.
- Kripalani, R. H., Kulkarni, A., Sabade, S. S., Khandekar, M. L., 2003. Indian Monsoon Variability in a Global Warming Scenario. Natural Hazards, 29, 189-206.
- Kudela, K., 2009. On energetic particles in space. Acta Phys. Slovaca, 59, 537-652.
- Kulmala, M., Asmi, A., Lappalainen, H. K., Carslaw, K. H., et al., 2009. Introduction: European Integrated Project on Aerosol Cloud Climate and Air Quality interactions (EUCAARI) - integrating aerosol research from nano to global scales. Atmos. Chem. Phys. 9, 2825-2841.
- Kumar K. K., Rajagopalan, B., Cane, A., 1999. On the weakening relationship between the Indian monsoon and ENSO. Science, 284, 2156-2159.
- Kumar, R. R., Kumar, K. K., Ashrit, R. G., Patwardhan, S. K., Pant, G. B., 2002. Climate Change in India. Shukla, J., et al., (Ed.), Tata McGraw Hill, New Delhi, India, 2475.
- Laken, B., Wolfendale, A., Kniveton, D., 2009. Cosmic ray decreases and changes in the liquid water cloud fraction over the oceans. Geophys. Res. Lett. 36, L23803.
- Laken, B. A., Kniveton, D. R., Frogley, M. R., 2010. Cosmic rays linked to rapid mid-latitude cloud changes. Atmos. Chem. Phys. 10, 10941-10948.
- Legras, B., Mestre, O., Brad, E., Yiou, P., 2010. A critical look at solar-climate relationships from long temperature series. Climate of the Past, 6, 745-758.
- Levin, Z., Ziv, A., 1974. The electrification of thunderclouds and the rain gush. J. Geophys. Res. 79, 2699.
- Marsh, N. D., Svensmark, H., 2000. Low Cloud Properties Influenced by Cosmic Rays. Phys. Rev. Lett. 85, 5004-5007.
- Mavrikis, A., Lykoudis, S., 2006. Heavy precipitation episodes and cosmic rays variation. Adv. Geosci. 7, 157-161.
- Neff, U., Burns, S. J., Mangini, A., Mudelsee, M., Fleitmann, D., Matter, A., 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6kyr ago. Nature, 411, 290-293.
- Palle, B. E., Butler, C. J., 2000. Cosmic rays and climate: The influence of cosmic rays on terrestrial clouds and global warming. Astron. Geophys. 41, 4.18-4.22.
- Pant, G. B., Parthasarathy, B., 1981. Some aspects of an association between the southern oscillation and Indian summer monsoon. Arch. Meteorol. Geophys. Bioklimatol. Ser. B, 29, 245251.
- Parker, E. N., 1999. Solar physics: Sunny side of global warming. Nature, 399, 416-417.
- Pruppacher, H. R., Klett, J. D., 1997. Microphysics of Clouds and Precipitation, (Second Revised and Enlarged Edition with an Introduction to Cloud Chemistry and Cloud Electricity), Kluwer Academic Publishers, Dordrecht, pp 954.
- Pudovkin, M. I., Veretenenko, S.V., 1995. Cloudiness decreases associated with Forbush decreases of galactic cosmic rays. J. Atmos. Terr. Phys. 57, 1349-1355.
- Rao, U. R., 1972. Solar modulation of galactic cosmic radiation. Space Sci. Rev. 12, 719-809.
- Rao, U. R., 2011. Contribution of changing galactic cosmic ray flux to global warming. Current Science, 100, 223-225.
- Rogers, R. R., Yau, M. K., 1989. A short course in cloud physics, Pergamon Press, Oxford.
- Ruzmaikin, A., Feynman, J., Yung, Y. L., 2006. Is solar variability reflected in the Nile River? J. Geophys. Res. 111, D21114.
- Rasmusson, E. M., Carpenter, T. H., 1983. The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. Mon. Weather Rev. 111, 517528.
- Shukla, J., 2007. Monsoon Mysteries. Science, 318, 204-205.
- Sikka, D. R., 1980. Some aspects of the large-scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary regional scale circulation parameters. Proc. Indian Acad. Sci. Earth Planet. Sci. 89, 179-195.
- Singh, A. K., Singh, D., Singh, R. P., 2011. Impact of galactic cosmic rays on Earth's atmosphere and human health. Atmos. Environ. 45, 3806-3818.
- Singh, Y. P., Badruddin, 2006. Statistical considerations in superposed epoch analysis and its applications in space research. J. Atmos. Solar-Terr. Phys. 68, 803-813.
- Sinha, A., Cannariato, K. G., Stott, L. D., Cheng, H., Edwards, R. L., Yadava, M. G., Ramesh, R., Singh, I. B., 2007. A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India. Geophys. Res. Lett. 34, L16707.
- Stozhkov, Yu. I., Zullo, J. Jr., Martin, I. M., Pellegrino, G. Q., et al., 1995. Rainfalls during great Forbush decreases. Il Nuovo Cimento C, 18, 335-341.

- Svensmark, H., Bondo, T., Svensmark, J., 2009. Cosmic ray decreases affect atmospheric aerosols and clouds. *Geophys. Res. Lett.* 36, L15101.
- Tinsley, B.A., 2008. The global atmospheric electric circuit and its effects on cloud microphysics. *Rep. Prog. Phys.* 71, 066801.
- Tiwari, M., Ramesh, R., Somayajulu, B. L. K., Jull, A. J. T., Burr, G. S., 2005. Solar control of southwest monsoon on centennial timescales. *Curr. Sci.* 89, 1583-1588.
- Usoskin, I. G., 2011. Cosmic rays and climate forcing. *Memorie della Societa Astronomica Italiana*, 82, 937-942.
- Venkatesan, D., Badruddin, 1990. Cosmic ray intensity variations in 3-Dimensional Heliosphere. *Space Science Review*, 52, 121-194.
- Verschuren, D., Laird, K. R., Cumming, B. F., 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature*, 403, 410-414.
- Yadava, M. G., Ramesh, R., 2007. Significant longer-term periodicities in the proxy record of the Indian monsoon rainfall. *New Astron.* 12, 544-555.